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**RESEARCH PAPER**

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# Management-related energy, nutrient and worktime efficiencies of the wood fuel production and supply chain: modelling and assessment

Nicolas Bilot<sup>1,2</sup> , Christine Deleuze<sup>3</sup> , Laurent Saint-André<sup>2</sup> , Yann Rogeau<sup>4,5</sup> , Meriem Fournier<sup>1</sup> and Holger Wernsdörfer<sup>1\*</sup>

## Abstract

**Key message** The modelling approach presented and tested in the present study relates local management decisions with efficiency indicators of the whole wood fuel chain, based on decisions ranging from silviculture to transport to customer. Energy and worktime efficiencies were better under large-scale energy production associated with high wood fuel demand, whereas nutrient efficiency was better under small-scale production associated with a moderate demand. Local management decisions all along the wood fuel chain highly influenced efficiency indicators, and thus its relevance for energy-transition policies.

**Context** Bioenergy from wood can contribute to reach the goals of energy-transition policies. Use of wood as fuel should focus on low-quality wood, e.g. by-products from timber production, which production and supply is related to various management decisions. Reaching the policy objectives efficiently remains an issue.

**Aims** The aims are (1) to develop a modelling approach that links local management decisions with indicators of the whole wood fuel production and supply chain and (2) to test the model in a case study. The study should further provide first insights on how indicators of energy, nutrient and worktime efficiency vary according to wood fuel chain characteristics and the related management decisions.

**Methods** The model depicts the flow of wood (biomass, nutrients, moisture content, heating value) from the forest stand to the heating plant for each silvicultural intervention simulated with a growth and yield model. It further quantifies the energy and worktime spent on different wood fuel chain tasks (e.g. felling, forwarding) set by the user. We defined four scenarios according to the scale of energy production (large vs. small) and the demand for wood fuel (high vs. moderate).

**Results** The case study revealed that the model outputs were plausible. Energy efficiency largely varied depending on the type of silvicultural intervention. Large-scale production associated with high demand was most favourable for

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energy and worktime efficiencies. In contrast, nutrient efficiency was best for small-scale production associated with moderate demand.

**Conclusions** Local management decisions all along the wood fuel chain highly influenced efficiency indicators, and thus its relevance for energy-transition policies. Our model may contribute to strategic decision making in different forestry and energy production contexts.

**Keywords** Energy, Wood, Model, Simulation, Demand, Production scale, Forest management, Forest operations

## 1 Introduction

Evidence of climate warming has led to an energy-transition policy aimed at increasing the share of renewable energy sources, as part of the European bioeconomy (EC 2018) and Green Deal (EC 2019) strategies. Bioenergy is expected to play a relevant role in reaching the share of renewables targeted by 2030, which is supposed to increase from 32 to 40% (EC 2021a). Bioenergy from wood can contribute to reach this goal. In France, it accounted for 33% of primary production of renewable energy in 2020 (Phan and Plouhinec 2021), mainly in the form of heat. Heat-energy production from biomass is supposed to increase by about 40 to 50% between 2018 and 2028 (from 112 to 157–169 TWh; Phan and Plouhinec 2021). While wood fuel has mostly been used as split logs in households so far, political measures implicitly foster also other types of wood fuel like chips or pellets. They include financial aids for the development of industrial and collective heat production from woody biomass and other renewables (ADEME 2020).

The development of energy production from wood should take place in line with available resources and environmental considerations. Harvesting wood primarily for energy use may cause undesired effects on climate change (Searchinger et al. 2018). Use as fuel should focus on low-quality wood that cannot be processed into products with a longer life time (EC 2021b), or with higher added value. This strategy is already implemented in traditional forest management in Europe, which is mainly focused on timber production, e.g. sawn timber for construction or furniture (FAO 2015). In that context, wood fuel can be provided as a by-product. Typical by-products are whole small trees from early silvicultural interventions or tree tops and branches. The latter remain after harvesting of stems for timber during late thinnings or final harvests. Transforming them into chips or other types of wood fuel and transporting them to the heating plant are subsequent tasks of the wood fuel production and supply chain (hereafter: WFC).

This study focuses on production and supply of wood fuel as chips from silvicultural by-products. Wood chips are supposed to have great potential as an alternative energy source in Europe, with observed shifts in the supply and process chains (Díaz-Yáñez et al. 2013). In

turn, production systems dedicated to wood fuel, such as short-rotation coppice, are not investigated here. Furthermore, we did not consider by-products from industrial processing or further-processed wood fuel types, e.g. torrefied pellets (Wolfsmayr and Rauch 2014; Yun et al. 2020).

The silvicultural by-products—especially fine woody debris (here: <7 cm in diameter over bark)—usually have high nutrient concentrations (Augusto et al. 2008b; André et al. 2010; Wernsdörfer et al. 2014). Their removal may decrease soil fertility and in turn forest production (Achat et al. 2015). Another concern is energy efficiency, i.e. the ratio of the energy contained in the wood fuel to the energy spent to produce and supply it (Hall et al. 1986). This is all the more important as this energy and related greenhouse gas emissions—e.g. to run harvesting machines—stems massively from fossil fuels. At last, worktime is an important component when it comes to assessing the efficiency of forest operations performed by human operators and machines (IUFRO 1995).

WFC management decisions can impact, to a certain extent, energy, nutrient and worktime efficiencies. In this respect, they may be crucial for reaching objectives of energy-transition policies. Measures aimed at limiting nutrient export include harvesting of broad-leaved trees when they are leafless, seasoning wood in the forest stand before forwarding (Achat et al. 2015), leaving fine woody debris partly in the forest depending on soil conditions (Landmann et al. 2018), or compensating with fertilisers (Samuelsson 2002; Kaye et al. 2008; Han et al. 2011) or wood ash (Augusto et al. 2008a; Brais et al. 2015). Seasoning or drying may additionally improve wood fuel quality. Quality (e.g. heating value, ash and dust contents) is related to the wood moisture content and the tree parts used as wood fuel (Nurmi 1993, 1997). The energy spent in the WFC can depend on tree size and bucking rules, the degree of mechanisation, the succession of WFC tasks, the transport distance and the related worktime. Finally, these relationships depend on the demand for wood fuel, in total and compared to other competing uses. For example, wood fuel and pulp wood can rely on the same tree parts. These are important issues for further research on the sustainability of biomass supply

chains (Ghaffariyan et al. 2017). The diversity of management options and local conditions requires models and scenario-simulation tools to depict and analyse the underlying complex relationships and to support decision making.

Models of biomass supply chain management commonly aim at assessing performance or efficiency, or at optimising components or schedules of supply chains (Nunes et al. 2020). They mostly depict mass flows or costs (Nunes et al. 2020). Some studies rely on discrete-event simulation using generic software programmes (Mobini et al. 2011; Windisch et al. 2015; Pinho et al. 2016). Methodological approaches to assess WFCs include lifecycle analysis (Lindholm et al. 2010; Valente et al. 2011), economic cost and market analyses (Gan and Smith 2011; Kallio et al. 2011; Kamimura et al. 2012), or multi-criteria analysis and optimisation (Kühmaier and Stampfer 2012; Kanzian et al. 2013; Shabani and Sowlati 2013; Sacchelli et al. 2014). Some studies combine several approaches or tools, including GIS for spatial analyses (Frombo et al. 2009; Kanzian et al. 2009; Perpina et al. 2009; Vainio et al. 2009). Few studies seem to have used forest growth and yield models at a large spatial scale (Kallio et al. 2013; Steubing et al. 2014) or at the forest stand scale (François et al. 2014). However, this may be relevant for addressing differences between silvicultural interventions throughout a forest production cycle because spatio-temporal variation of resources is an important feature of biomass supply chains (Nunes et al. 2020).

WFCs, or parts of them, have been depicted with different levels of detail. Aggregated approaches rely on condensed information from sources such as databases or external, partial-chain models (Lindner et al. 2010; Martire et al. 2015). More detailed approaches often come with work measurements such as time studies that decompose forest operations into successive tasks and elements (Akay et al. 2004; Kärhä et al. 2004; Cremer and Velazquez-Marti 2007; Spinelli et al. 2010). They can rely on explicit parameters like product assignment or choice and consumptions of machines. Consequently, individual tasks and associated local management decisions, as depicted by explicit parameters, can be related to energy, nutrient and worktime efficiencies of the WFC as a whole. This requires associating knowledge of forest, wood and energy sciences in a consistent manner. Developing such bottom-up approaches may contribute to closing the gap between theoretical models and current practices in biomass production and supply (Mafakheri and Nasiri 2014). The overall question to be answered is how energy, nutrient and worktime efficiencies vary according to WFC characteristics and the related management decisions.

Our first objective was to develop a bottom-up modelling approach for the WFC of forest-wood chips, ranging from forest production to chips delivery to the plant. The WFC model should be suitable for silvicultural systems where wood fuel is a by-product of timber production, which are depicted through growth and yield modelling. The model should additionally meet the following requirements:

- (1) Consistency when it comes to depicting flows of woody material and the related management decisions. This requires similar principles and levels of detail of calculation between the different tasks and processes of the WFC (e.g. felling, seasoning);
- (2) Modularity so as to consider any kind of task and to choose the succession of tasks or processes where applicable. For example, seasoning can occur in the forest stand or on the roadside;
- (3) Genericness so as to simulate various silvicultural situations and schedules. Genericness is also a criterion for task modelling, which should allow the user to select different types of machines.

The present work provides a detailed description of the model, as opposed to the sole general approach summarised so far (Bilot 2014).

Our second objective was to test the performance of the model in a case study. The focus was on the comparison of contrasted WFC scenarios in relative terms. We parametrised the model for European beech (*Fagus sylvatica* L.), one of the major broadleaved tree species in Western and Central Europe.

## 2 Material and methods

### 2.1 Model description

#### 2.1.1 Modelling approach and functioning principles

Our WFC model depicts the flow of woody material from the trees cut in a forest stand up to chip delivery to a heating plant, as well as the energy and worktime spent on the different tasks. The spatial perimeter of forest operations includes the forest stand, transport distance to bring forest operators and machines to the forest stand, and transport distance to deliver wood fuel to the customer. The perimeter from a lifecycle perspective includes energy consumptions for machine operation, for machine building, maintenance and recycling (BMR) and for transport. Machine-specific consumptions are set by the user, so that BMR consumption may exclude or include upper lifecycle consumptions such as metal extraction for machine building.

The WFC is defined by successive tasks. The approach is inspired by work studies (IUFRO 1995), where a work task is defined as follows: “A clearly defined and

limited amount of work. When the output of production is material, the work task specifies the change of a physical form, the *work object*, from a clearly defined initial state to a clearly defined end state.” (IUFRO 1995, p 5). The model user can choose among different tasks (Table 1) and define their sequence according to the scenario to be simulated. Each task is depicted by a sub-model, i.e. a distinct part of the entire model. For example, a chipping task relies on a technical process run by an operator to transform pieces of wood (logs, branches, small trees) into chips. Natural processes in the WFC are seasoning (for roundwood) or drying (for chips). For the sake of simplicity, tasks and processes are both referred to as tasks hereafter. Two segments are defined within the WFC. The forest harvesting segment ranges from the forest stand to the forest roadside, and the processing and delivery segment from the forest roadside to the heating plant. The forest harvesting segment distinguishes between three main product types: timber, industry wood and wood fuel. Industry wood is roundwood for mechanical or chemical degradation, to produce panels or pulp, for instance. The total biomass and nutrient exports are quantified, as well as the export shares related to each product type. The processing and delivery segment only accounts for the material assigned to energy use. It is used together with the other segment to calculate energy and work-time efficiencies.

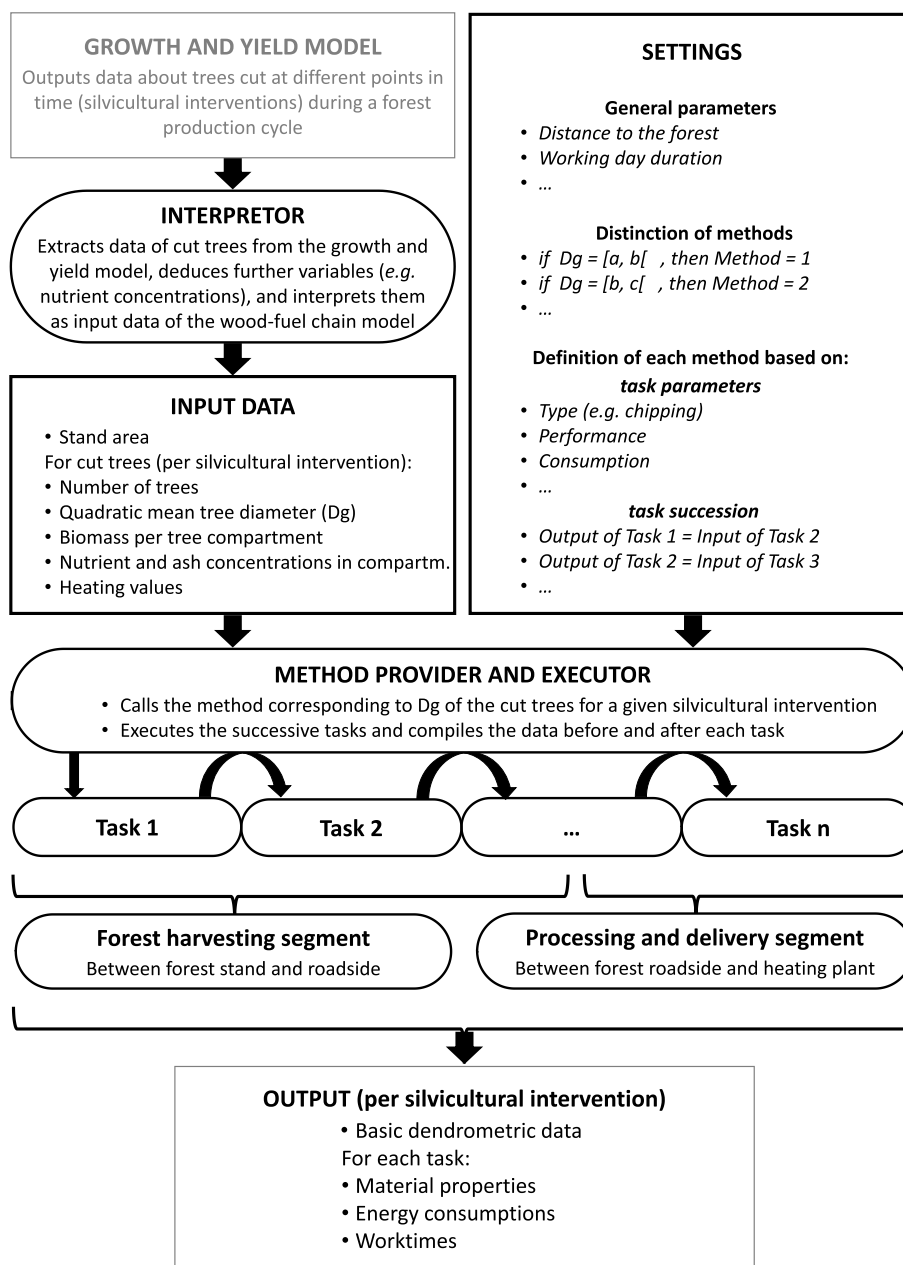
An overview of the inputs, settings, calculation principles and outputs is provided in Fig. 1. A detailed model description can be found in Appendix 1. Input data come from a growth and yield model that can be run according to different silvicultural schedules. They characterise the stand and the trees cut for the different silvicultural interventions made throughout a forest production cycle, which lasts from regeneration until final harvest. Trees are characterised by their

number, quadratic mean diameter ( $D_g$ ) and material properties *per* tree compartment. Settings define a given scenario of the WFC. They include the general parameters used for the whole simulation (e.g. distance to the forest), and specific sub-sets of tasks so-called “methods”. A method sets the task parameters (e.g. type and performance of machines) and the succession of tasks for a given  $D_g$ -range of the cut trees. Thus, appropriate methods of harvesting, processing and delivery can be defined according to tree size. For example, a feller-buncher can be used for felling small trees during early thinnings, while chainsaw felling is required for big trees during final harvest. During a simulation run, the tree data of a given silvicultural intervention are assigned to a method according to the  $D_g$  of the cut trees, and input in the first task of the chain. The output of the first task is used as the input of the second task, and so on, until the last task is performed. In this way, the model calculates modifications of the form of the material (e.g. processing of logs into chips), its properties, including material losses. The related worktimes and energy consumptions are calculated. The final model output is provided for each silvicultural intervention and related tasks. It includes basic dendrometric data, material properties (biomass, nutrient mass, heating value, ash content) and energy consumption and worktime of human operators and machines.

The model is implemented in the CAPSIS software platform (Dufour-Kowalski et al. 2012) under the name ForEnerChips. It was first connected to Fagacées (Le Moguédec and Dhôte 2012), an individual-tree-based growth and yield model for even-aged beech stands in northern France. Specific sub-models provided estimates of biomass (Genet et al. 2011) and nutrient concentrations (Wernsdörfer et al. 2014), hence of nutrient mass for the different tree compartments.

**Table 1** Name and description of the tasks depicted in the model

Task name	Task description
Felling	Fells trees chosen according to a given silvicultural schedule
Bucking	Debranches the felled stem, cuts logs and branches
Felling+bucking	Combined felling and bucking
Bundling	Compacts branches and twigs into bales
Seasoning	For roundwood left at a given place for a given timespan: reduces moisture content and accounts for dry material loss, reflecting residual cell respiration and biochemical degradation
Forwarding	Moves wood from the forest stand to the forest roadside
Chipping	Chops tree parts into small pieces
Drying	For chips left at a given place for a given timespan: reduces moisture content and accounts for dry material loss
Handling	Handles material without changing its geographical location, e.g. unloading of a truck
Transport	Moves material from the forest roadside to a platform or the heating plant



**Fig. 1** Construction principle of the model for wood fuel production and supply

**2.1.2 Task sub-models**

Sub-models for individual tasks rely on similar principles and levels of detail of calculation to ensure consistency between tasks. Input parameters are defined so as to reflect relevant data characterising forest operations and related management decisions. Consumptions are assessed according to five items: motor fuel; oil; transport of forest operators; transport of machines; machine BMR.

The tasks involving machines and material losses rely on the same equations. They include felling, bucking, bundling, forwarding, chipping and handling. Consumptions of these tasks are related to the amount of biomass to be treated, and to the required worktime of humans and machines. When several product types are distinguished, consumptions are allocated as follows: felling consumption is allocated to one of the product types (here: wood fuel); bucking consumptions are shared



between product types proportionally to their biomass share in accordance with methodology of lifecycle assessment (Jungmeier et al. 2002); forwarding occurs separately for each product type. The parameters have task-specific values including, e.g. performance or hourly motor-fuel consumption of machines.

Transport is considered to occur without any losses. The consumptions of this task are related to the total amount of wood to be delivered and to the maximum load *per* trip. The parameters include, e.g. load capacity and motor-fuel consumption *per* unit distance of the device (e.g. road truck), and delivery distance.

Seasoning and drying are passive processes without energy consumption. Moisture and dry material losses rely on the same equations deduced from literature (Deleuze et al. 2001; Ast 2009; Laurila and Lauhanen 2010), but on partly different parameter values. We chose simple model formulations, depending on the duration of seasoning or drying and on pile sheltering (covered or uncovered), for the sake of consistency with the level of detail of the other tasks.

Sub-models of seasoning and drying provide plausible outputs up to a duration of about 6 months. The moisture decrease can become too high over longer periods. Plausible outputs are expected for the other sub-models given the formulations of the equations (Appendix 1). However, uncertainty can arise depending on the data available to set input parameter values (Section 2.2).

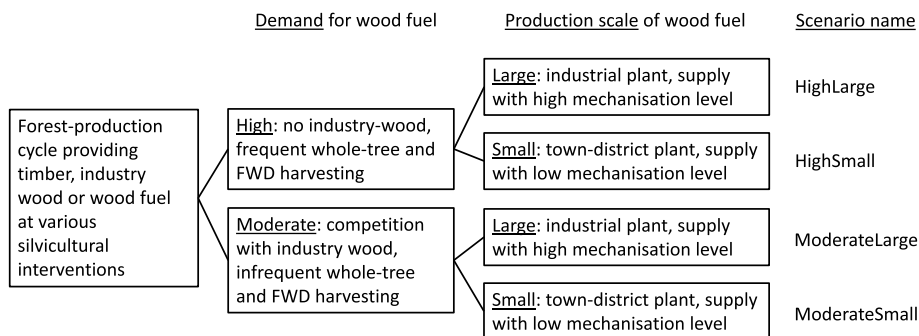
### 2.2 Case study

One forest production cycle of 111 years was simulated for a 5-ha beech stand managed according to the Lorraine region guidelines of the French National Forest Service, assuming a medium level of site fertility (ONF 2005). The main objective was to produce timber from trees with a 60–65-cm target diameter at breast height (dbh). Wood fuel and industry wood were by-products.

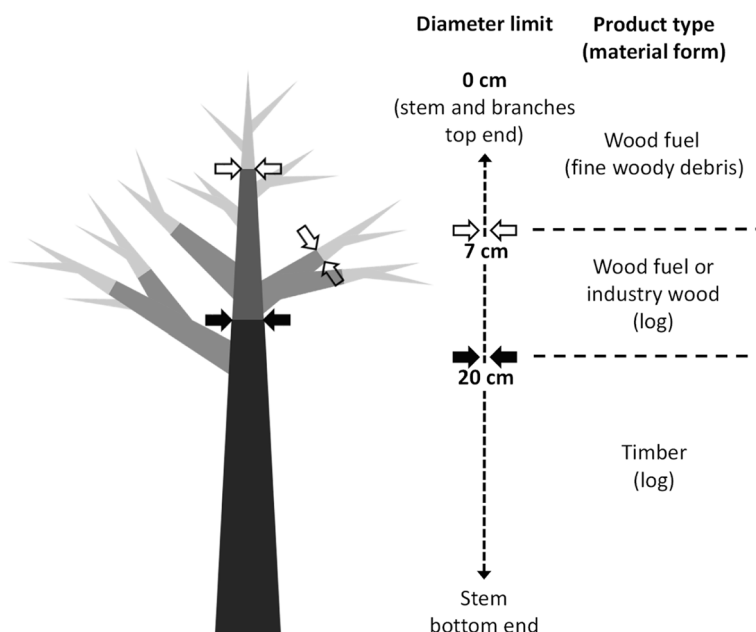
Stand establishment was followed by several successive phases: a growth enhancement phase of the most promising trees after pre-commercial thinning; a competition phase to enhance natural pruning; a heavy thinning phase to enhance growth until the target dbh was reached; a final harvesting phase. Twelve interventions were performed. The first one—pre-commercial thinning—took place in year 18, i.e. 18 years following regeneration. The interventions in years 36, 42 and 48 only provided small trees usable for wood fuel. Years 54 and 63 provided stems that were large enough for industry wood. Years 72, 81, 90, 99, 105 and 111 provided big trees whose stems were useable as timber. The bigger parts of the crowns of these trees were assignable to industry wood or wood fuel. Alternatively, the entire crown (including bigger parts and fine woody debris) was potentially useable for energy. Years 99, 105 and 111 corresponded to the phase of final harvest that took place in three interventions. The characteristics of the silvicultural schedule with the different interventions are presented in Fig. 4 of Section 3.

Four WFC scenarios were defined by combining two sub-scenarios of wood fuel demands with another two sub-scenarios of energy production scales (Fig. 2; see Appendix 2 for model settings and parameters). Wood fuel demand influenced the assignment of the tree compartments to the product types (Fig. 3). Different scales of energy production implied different WFC characteristics.

- For the high-demand sub-scenario, we assumed very high demand for wood fuel that outcompeted industry wood supply. Fine woody debris was assigned to energy use all along the forest production cycle. Whole trees were assigned to wood fuel until year 63. Then, stem parts  $\geq 20$  cm in diameter (top end, over bark) were assigned to timber, while the entire crown was assigned to wood fuel. Log length or timber quality criteria were not accounted for because the tree compartments were defined by



**Fig. 2** Overview of the four simulated WFC scenarios, based on an entire forest production cycle according to a common silvicultural schedule for European beech (ONF 2005)



**Fig. 3** General rules for the assignment of tree compartments to product types. The choice of the tree compartments to be assigned as products or left in the forest depends on the scenario

their cutting diameter in the biomass sub-models (Genet et al. 2011).

- For the moderate-demand sub-scenario, we assumed competition between wood fuel and industry wood for non-timber roundwood  $\geq 7$  cm in diameter. Harvesting of fine woody debris occurred only once during the production cycle to limit nutrient export (Landmann et al. 2018). Whole trees were assigned to energy in year 36. Industry-wood logs were bucked in stems  $\geq 7$  cm in diameter in years 54 and 63. Stem parts  $\geq 20$  cm in diameter were assigned to timber from year 72 onwards. In addition to the timber stem parts, crown parts  $\geq 7$  cm in diameter were assigned to wood fuel in the last three interventions (final harvesting phase).
- For the large-scale energy production sub-scenario, we assumed that an industrial plant was fed from forest stands located within a radius of about 100 km. The mechanisation level was high. The forest harvesting contractors used large forest machines. Wood was seasoned on the roadside and then chipped with a powerful chipper. Chips were transported by road trucks to customer.
- For the small-scale energy production sub-scenario, we assumed a medium-sized (European scale) municipality feeding a district heating plant with wood from the local forest. The mechanisation level was low. Wood was seasoned in the stand. The municipality used a chipper trailer adapted to

a farm tractor for forwarding, and an agricultural trailer for the short-distance transport to the heating plant.

The four scenarios were called HighLarge, HighSmall, ModerateLarge and ModerateSmall. For example, HighLarge means high demand combined with large-scale production. The complete factorial design allowed us to assess the variation of the WFC efficiencies (second objective). The HighLarge and ModerateSmall scenarios were likely most pertinent in practice. We focused on basic tasks of the beech WFC for the first analysis with our model. Thus, bundling, drying and handling did not occur in the case study. Bundling appears suitable only under certain conditions (Ghaffariyan et al. 2017) and was created for more specific case studies. Handling and drying could be added when analysing a more complex WFC including other components like chip storage on a platform.

Input parameter values (Tables 4, 5, 6 and 7 in Appendix 2) were first deduced from the literature (e.g. Spinelli et al. 2004; Ghaffarian et al. 2007; Laitila 2008; Lindholm et al. 2010; Yoshida et al. 2016) and then tuned based on expert knowledge. Parameter tuning was considered necessary to adapt values from different countries or tree species to the context of the case study and to ensure consistency among scenarios.

The four scenarios were assessed for (i) the entire forest production cycle and (ii) a given silvicultural intervention. We chose the final cut at 111 years of age as



a typical intervention where wood fuel is a by-product of timber production. Consumptions and worktimes related to non-harvested silvicultural interventions and to timber or industry wood were not accounted for. Wood-fuel-related consumptions were calculated after subtracting losses during felling and forwarding, and before subtracting losses during bucking and chipping.

### 2.3 Assessment indicators

We chose two sets of indicators. The first set assessed material flows related to forest harvesting. The second one assessed the efficiency of the energy supply to the heating plant for the WFC as a whole.

Forest harvesting-related indicators included:

- Assignment intensity:

$$AI = \frac{\text{Material}_{\text{Assigned}}}{\text{Material}_{\text{Marked}}} \text{ (no unit)}, \quad (1)$$

where  $\text{Material}_{\text{Assigned}}$  is the total dry biomass of the tree compartments assigned as a product.  $\text{Material}_{\text{Marked}}$  is the total aboveground dry biomass of the trees marked to be felled;

- Harvesting efficiency:

$$HE = \frac{\text{Material}_{\text{Forwarded}}}{\text{Material}_{\text{Assigned}}} \text{ (no unit)}, \quad (2)$$

where  $\text{Material}_{\text{Forwarded}}$  is the total dry biomass that was actually forwarded, i.e. after subtracting losses during the successive forest tasks. HE was calculated both in total for all product types and for the sole wood fuel.

Whole-WFC indicators included:

- Energy Return On Investment (EROI; Hall et al. 1986), also termed energy efficiency:

$$\text{EROI} = \frac{\text{LHV}_{\text{Delivered}}}{E_{\text{Consumed}}} \text{ (no unit)}, \quad (3)$$

where  $\text{LHV}_{\text{Delivered}}$  is the total energy content (lower heating value, LHV) of the material (here: chips) delivered to the heating plant.  $E_{\text{Consumed}}$  is the total energy consumed to provide this material;

- Biomass Energy Nutrient Efficiency:

$$\text{BENE} = \frac{\text{Material}_{\text{Removed}}}{\text{LHV}_{\text{Delivered}}} \text{ (kg MWh}^{-1} \text{ or g MWh}^{-1}\text{)}, \quad (4)$$

where  $\text{Material}_{\text{Removed}}$  is the biomass (fresh or dry) or nutrient mass of the wood fuel removed from the forest stand;

- Biomass Energy Worktime Efficiency:

$$\text{BEWE} = \frac{\text{Worktime}}{\text{LHV}_{\text{Delivered}}} \text{ (h MWh}^{-1}\text{)}, \quad (5)$$

where Worktime is the cumulated human and machine worktime associated with all tasks.

EROI, BENE and BEWE were calculated *per* silvicultural intervention, excluding interventions or tasks that did not provide wood fuel.

## 3 Results

### 3.1 Assessment of the entire forest production cycle

WFC energy consumption at high demand was approximately three times as much as consumption at moderate demand (Table 2). While differences in energy consumption between production scales were small for moderate demand, they were noticeable for high demand. Similar orders of magnitude were obtained for the energy delivered to the heating plant. The lower heating value of chips for high demand was approximately three times the value for moderate demand. It was highest for large-scale production. Wood fuel quality in terms of energy *per* biomass and ash concentrations was similar across all four scenarios.

EROI was mostly influenced by wood fuel demand. In high-demand scenarios, EROI was about 13 to 23% higher for the entire production cycle, and about 22 to 36% higher for the final harvesting phase, as compared to moderate demand scenarios. For a given scenario, EROI values were similar for the final harvesting phase, but varied between thinnings (high demand; Table 2).

The high-demand scenarios had on average the most favourable energy balance (EROI), but they were less efficient when it came to nutrient export (BENE for N, S, P, K, Ca, Mg and Mn; Table 2). This was especially the case for the HighLarge scenario: lower BENE values indicated better nutrient efficiency as less nutrients were exported for the same amount of energy delivered. The BENE values for nutrients of the HighLarge and ModerateSmall scenarios clearly differed by up to 34 and 32% for N and P,

**Table 2** Assessment for a 5-ha stand of European beech throughout the entire forest production cycle. Energy summary indicators are cumulated values, whereas the other indicator values are means or ranges *per* silvicultural intervention. Thinning phase: 36–90 years of stand age; harvesting phase: 99–111 years of stand age

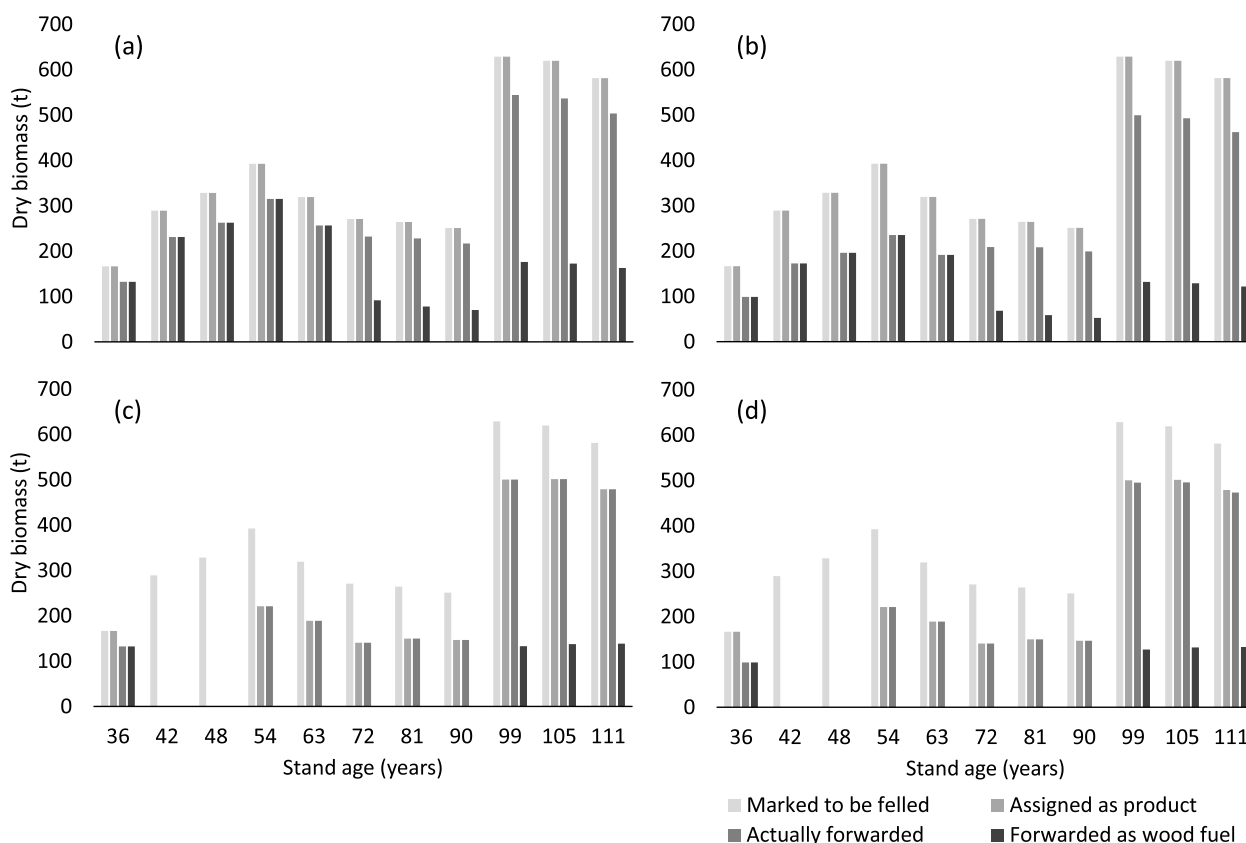
	Wood fuel demand: Scale of production:	High		Moderate	
		Large	Small	Large	Small
<b>Energy summary</b>					
Energy (LHV) delivered	<i>kWh ha<sup>-1</sup></i>	1,598,635	1,243,606	443,693	419,558
Ash content (delivered)	<i>kg ha<sup>-1</sup></i>	2322	1756	606	566
Energy consumed	<i>kWh ha<sup>-1</sup></i>	93,661	81,086	28,510	27,916
<b>Wood fuel quality</b>					
Energy (LHV) <i>per</i> biomass	<i>kWh t<sup>-1</sup></i>	3105	3105	3104	3104
Ash concentration	<i>g kg<sup>-1</sup></i>	6.8	6.6	6.5	6.4
<b>EROI</b>					
Forest production cycle	<i>no unit</i>	22.2	23.3	19.6	19.0
Thinning phase (min-max)	<i>no unit</i>	7.6–28.7	6.3–31.4	7.6–7.6	6.3–6.3
Final harvesting (min-max)	<i>no unit</i>	28.5–29.0	31.5–31.7	23.4–23.7	23.2–23.2
<b>BENE</b>					
Fresh mass	<i>kg MWh<sup>-1</sup></i>	488	358	488	358
Dry mass	<i>kg MWh<sup>-1</sup></i>	244	234	244	234
Carbon (C)	<i>kg MWh<sup>-1</sup></i>	116	112	116	112
Nitrogen (N)	<i>g MWh<sup>-1</sup></i>	405	336	327	303
Sulphur (S)	<i>g MWh<sup>-1</sup></i>	40	36	36	34
Phosphorus (P)	<i>g MWh<sup>-1</sup></i>	37	30	30	28
Potassium (K)	<i>g MWh<sup>-1</sup></i>	347	318	325	309
Calcium (Ca)	<i>g MWh<sup>-1</sup></i>	338	320	315	304
Magnesium (Mg)	<i>g MWh<sup>-1</sup></i>	57	54	55	53
Manganese (Mn)	<i>g MWh<sup>-1</sup></i>	55	52	53	51
<b>BEWE</b>	<i>h MWh<sup>-1</sup></i>	0.34	0.55	0.49	0.78

respectively. Those of the HighSmall and ModerateLarge scenarios were rather similar. Differences between BENE values were relatively small for Mg and Mn. As regards fresh and dry mass and carbon, BENE values were about the same for the two large-scale scenarios and the two small-scale scenarios. The small-scale scenarios had more favourable (lower) BENE values. The most favourable BENE values were altogether found for the ModerateSmall scenario.

Efficiency in terms of worktime (BEWE) was best in the HighLarge scenario that had the lowest BEWE value (Table 2). It was worst in the ModerateSmall scenario, whose BEWE value was more than twice that of the HighLarge scenario.

Figure 4 shows the biomass flow within the forest harvesting segment for each silvicultural intervention. Four stages of biomass flow are distinguished: standing trees (aboveground part) marked to be felled; tree compartments assigned as a product to be harvested; total actually harvested and forwarded wood; and forwarded wood fuel. The amount of biomass marked to be felled resulted from silvicultural management, which was the same for

all case study scenarios. Felled trees remained in the stand as unharvested in years 42 and 48 in the moderate-demand scenarios. The highest amounts of biomass were harvested during the last three interventions, resulting in complete removal of the adult stand. This final harvesting phase can be considered as the starting point of a new forest production cycle. As regards the average values of all silvicultural interventions, assignment intensity amounted to 99 and 60% for the high- and moderate-demand scenarios, respectively. Total harvesting efficiency for all product types was lower in the high-demand scenarios (84 and 72% for large- and small-scale production, respectively) than in the moderate-demand scenarios (99 and 97%, respectively). This was related to fine woody debris harvesting, which occurred only once during the forest production cycle in the moderate-demand scenarios. Fine woody debris harvesting resulted in relatively high losses as small branches and twigs were assumed to break off more easily than other tree compartments. For a given demand, harvesting efficiency was higher for large-scale than for small-scale production. Small-scale production resulted in higher losses because



**Fig. 4** Material flow within the forest harvesting segment for each silvicultural intervention in a 5-ha stand of European beech. Results are plotted for the HighLarge (a), HighSmall (b), ModerateLarge (c) and ModerateSmall (d) scenarios

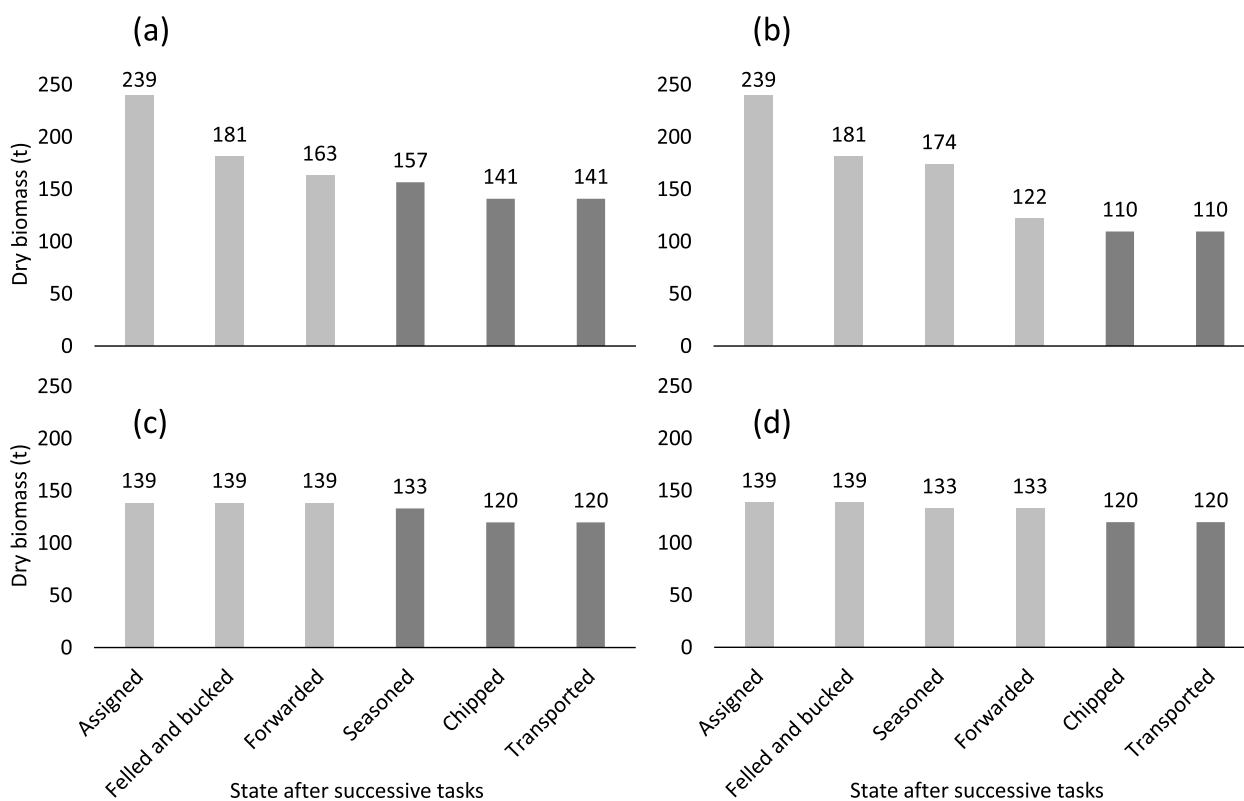
seasoning occurred before forwarding, and branches and twigs were assumed to break off more easily during forwarding. Harvesting efficiency of wood fuel was lower than total harvesting efficiency (HighLarge: 75%; High-Small: 56%; ModerateLarge: 94%; ModerateSmall: 85%). This was related to the fact that small tree compartments were assigned to wood fuel.

### 3.2 Detailed assessment of wood fuel for the final cut

This section focuses on the supply of wood fuel from the final cut at 111 years of age. Felling, bucking and forwarding resulted in biomass losses in the high-demand scenarios, but not in the moderate-demand scenarios (Fig. 5). As mentioned above, this was related to fine woody debris harvesting in the high-demand scenarios, where felling and bucking resulted in a 24% loss of the biomass assigned to wood fuel. The seasoning process itself led to a ~4% biomass loss compared to the previous task for all scenarios. Harvesting efficiency varied according to the position of seasoning along the WFC. In the high-demand scenarios, it was 68 or 51% depending on whether seasoning took place after forwarding (large-scale production) or before forwarding (small-scale

production), respectively. Harvesting efficiency was clearly higher for moderate demand as no fine woody debris was assigned to wood fuel at 111 years of age. It was 100 and 96% for large- and small-scale production, respectively. All in all, the ratios of the amount of biomass finally transported to the heating plant to the amount of biomass assigned to wood fuel in standing trees were 59, 46, 86 and 86% in the HighLarge, HighSmall, ModerateLarge and ModerateSmall scenarios, respectively.

Energy consumption (Fig. 6) was clearly lowest for felling and bucking in all four scenarios. This was related to the fact that chainsaws were used, given the high dbh ( $D_g = 71$  cm) of the trees to be cut. Consumption by felling and bucking was higher for moderate demand, consistent with the fact that branches were cut in order to exploit only those parts with a diameter  $\geq 7$ cm. In contrast, whole branches were harvested for high demand. Consumptions of the other tasks (Fig. 6) varied across scenarios depending on the amount of biomass (Fig. 5) to be processed and on machine-specific parameters. For example, machine performance varied depending on whether entire branches (high-demand scenarios) or branch parts (moderate-demand scenarios) were



**Fig. 5** Material flow of wood fuel within the WFC for the last silvicultural intervention at 111 years of age in a 5-ha stand of European beech. Light grey: forest harvesting segment; dark grey: processing and delivery segment. Results are plotted for the HighLarge (a), HighSmall (b), ModerateLarge (c) and ModerateSmall (d) scenarios

forwarded. As a result (Fig. 6), forwarding was the most energy-demanding task in all scenarios but the High-Small scenario. Chipping consumption was higher for small-scale than for large-scale production. Transport consumption was clearly higher for large-scale production, in line with the higher transport distance compared to small-scale production.

Among the four items, motor fuel represented an average 86% of total consumption *per* task. The percentage of motor fuel consumption ranged between 52% (large-scale production) and 70% (small-scale production) for felling and bucking. It was around 90% for forwarding and chipping, and nearly 100% for transport.

## 4 Discussion

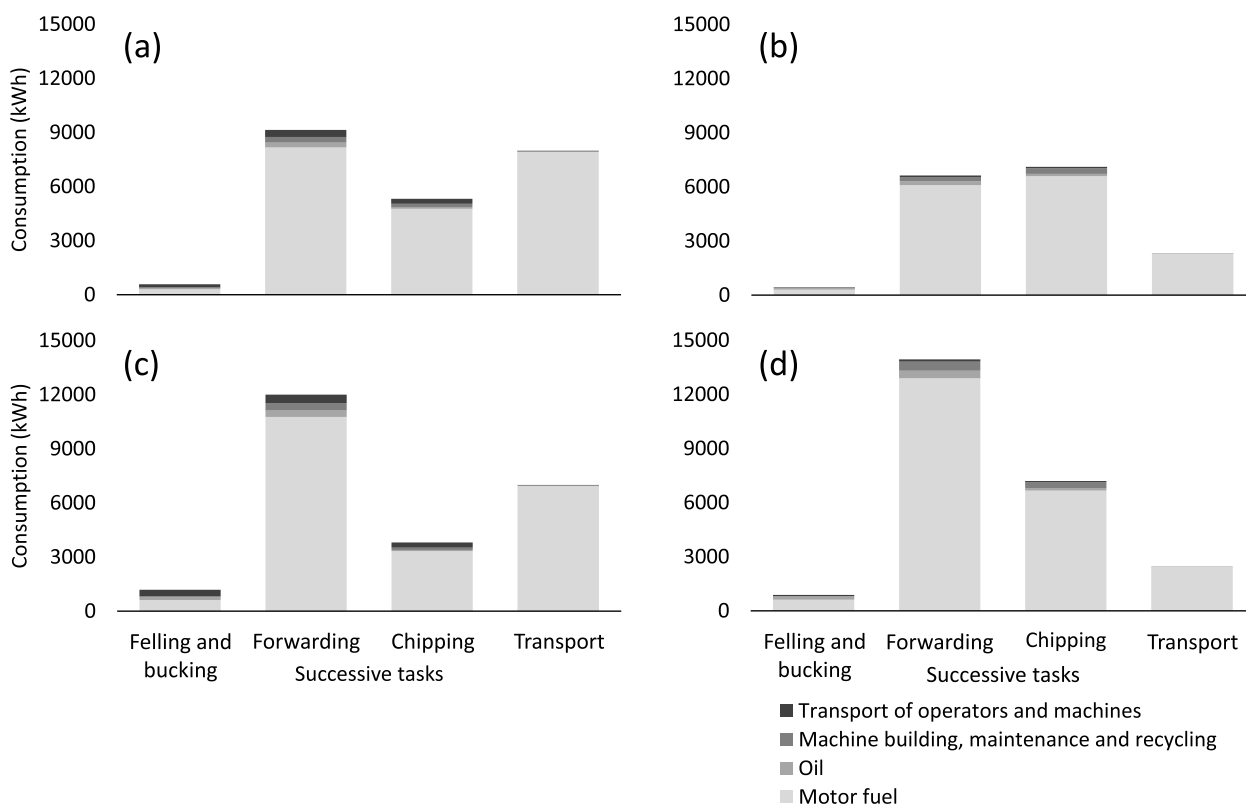
### 4.1 Case study

The energy content (LHV) of about 3100 kWh t<sup>-1</sup> (Table 2; moisture content = 0.345) found in our study was within the order of magnitude of literature values on wood chips. Gingerich and Hendrickson (1993) used 10.5 MJ kg<sup>-1</sup> (about 2920 kWh t<sup>-1</sup>) in their study. Pandur et al. (2015) found 11.17 GJ t<sup>-1</sup> (about 3100 kWh t<sup>-1</sup>) for oak wood chips with 35% moisture content. Moskalik and Gendek (2019) reported a range of 8.7–12.9 MJ kg<sup>-1</sup>

(~2420–3580 kWh t<sup>-1</sup>) for a moisture content-range of 47.1–27.7%.

In contrast, the ash concentration of about 0.7% (Table 2) was relatively low (Dupont et al. 2010; Moskalik and Gendek 2019). The latter authors reported ~3–4% for chips from logging residues, and 1–2% lower values for chips from branches and whole trees. Thus, the sub-model of the ash concentration (Appendix 1) should be subjected to further analyses. Furthermore, the allocation of felling consumptions may be improved in a future version of the model. For the sake of simplicity, they are allocated to one product type—wood fuel—in the case study. Thus, wood-fuel-related felling consumptions are overestimated when several product types are assigned. However, the case study focused on comparing scenarios in relative terms, so that we did not expect these biases to have relevant impact on the results.

Forwarding required the highest amount of energy at final harvest in three out of four scenarios (Fig. 6). Moreover, consumptions varied according to the mechanisation level (large- vs. small-scale production scenarios) and to wood fuel demand and the related material form (high- vs. moderate-demand scenarios). This suggests that management decisions on forwarding can be particularly



**Fig. 6** Energy consumptions within the WFC for the last silvicultural intervention at 111 years of age in a 5-ha stand of European beech. Results are plotted for the HighLarge (a), HighSmall (b), ModerateLarge (c) and ModerateSmall (d) scenarios

relevant to ensure energy efficiency. Furthermore, total consumption was clearly sensitive to transport distance and the related type of vehicle (large- vs. small-scale production; Fig. 6). Transport distance is known to be a major factor of the energy balance (Gingerich and Hendrickson 1993; Pandur et al. 2015). We can note that the transport distance of the large-scale scenario was within the range of economically viable transport distances according to the review by Moskalik and Gendek (2019), who reported distances of 50–100 km and 150 km for chips from logging residues and roundwood, respectively.

Energy consumptions, and hence EROI values, only provide a rough picture because the items taken into account vary between studies. Gingerich and Hendrickson (1993) only considered motor fuel and oil. Pandur et al. (2015) additionally accounted for machine building, maintenance and recycling, similar to our study. Some studies included other items such as pesticide production (Pandur et al. 2015) or road building (Murphy et al. 2014). Nevertheless, motor-fuel consumptions appeared to remain the most important factor. They amounted to 86% on average at final harvest in our study, and to 82 and 86% in the studies by Klvac et al. (2003) and Pandur et al. (2015), respectively. However,

the share of motor-fuel consumptions can highly vary across tasks. It ranged from 52% to nearly 100% at final harvest according to our results.

The EROI values in our study were roughly in accordance with literature values. Means of silvicultural interventions ranged between *ca.* 19 and 23 depending on the scenario (Table 2). An EROI of 22.4 was reported by Nikodinoska et al. (2017) for wood chips supply from selective cuttings in close-to-nature forest management of conifer-dominated stands. Pandur et al. (2015) deduced an EROI of 30 from the literature as an order of magnitude for wood fuel. They found an EROI of about 25 for wood chips from final harvests of oak stands. Our results also showed that EROI values can highly vary between silvicultural interventions. They were as low as about 6–8 for early thinnings and as high as about 29–32 (high demand) in the final harvesting phase (Table 2). An even higher EROI (38) has been reported for the harvesting of logging residues from conifer stands that excluded felling but included a loading task (Lindholm et al. 2010). This highlights the importance of accounting for the type of silvicultural intervention, product assignment and types of tasks when assessing EROI. Analysing alternative

silvicultural schedules could provide further insights in this respect (see Section 4.2).

Our results were within the range found in the literature for exported nutrient mass of European beech. The mean exported nutrient mass *per* silvicultural intervention increased by 36–62% for large-scale production and 11–22% for small-scale production between the moderate- and the high-demand scenarios (ranges reflect different nutrients; data not shown in Section 3). For the same tree species, François et al. (2014) compared fine woody debris harvesting with standard practices where only branches  $\geq 7$  cm in diameter were harvested. They found 5–8% increases in nutrient (N, S, P or K) exports over a longer production cycle of 140 years, and 11–13% increases over a shorter one of 100 years. Harvesting branches in addition to stems changed nutrient (N, P, K, Ca or Mg) exports by +9 to +26% in the study by Achat et al. (2018), and by –1 to +24% when the target diameter was reduced from 60 to 40 cm. Taking stem-only harvesting as a reference, André et al. (2010) reported a 34–61% increase in nutrient (P, K, Ca, or Mg) exports for additional harvesting of branches  $\geq 7$  cm in diameter, and a 65–162% increase for whole tree harvesting (i.e. additional harvesting of branches including fine woody debris; figures for beech and oak). This highlights that nutrient export for a given tree species highly depends on the silvicultural schedule, types of interventions and on product assignment, which are taken into account interactively in our model.

For BENE of nutrients, the highest relative differences between scenarios were for N and P (Section 3.1). These nutrients are crucial for assessing soil conditions related to forest productivity (Bontemps and Bouriaud 2014). Thus, the sustainability of the HighLarge scenario may be questioned. This appears even more important as measures of compensatory fertilisation or liming may only be economically feasible for relatively high wood fuel prices (Paillet et al. 2013). BENE identified the WFC scenario that delivered a given amount of energy in the most nutrient-efficient way (ModerateSmall). With this scenario, potential additional costs for nutrient compensation can be limited.

Worktime efficiency can be interpreted in terms of employment and cost. For a given wood fuel demand, large-scale production with a higher mechanisation level was more efficient when it came to worktime (BEWE; Table 2). In line with this, full-time employment is reported to be lower for higher levels of mechanisation (Martire et al. 2015). In turn, the number of full-time jobs is reported to be higher when more biomass is used (Martire et al. 2015). Nevertheless, for a given production scale, providing a higher amount of wood fuel in the high-demand scenarios can still require relatively

little worktime when considering the amount of delivered energy (Table 2). Moreover, potential employment should be compared with the available workforce, which may be limited (e.g. loggers; Valente et al. 2011). Referring to the small-scale production scenario, we may assume that the workforce is available locally in the municipality. However, using this workforce may be questioned from an economic point of view (labour and machine operation costs), especially when wood fuel demand is moderate (Table 2). Worktime is also an aspect involved in social lifecycle analysis as a complementary approach, which would allow for the assessment of social implications in a regional socio-economic context (Siebert et al. 2018; Bezama et al. 2021).

Finally, the ModerateSmall scenario was least favourable as to energy and worktime efficiency. Certain policymakers or environmental actors may attach great importance to the better nutrient efficiency of this scenario (BENE; Table 2). They may also attach importance to soil protection through the use of lighter machines (Ampoorter et al. 2012) expected in small-scale production, or to social acceptance of different forest operation techniques. Our model provides relevant knowledge for decision making which will finally depend on the objectives and preferences of the actors involved in the process.

In a larger sense, our case study highlights crucial, general aspects for the use of wood as an energy resource and related policies. WFC efficiency can highly vary depending on the type of silvicultural intervention, product assignment, harvesting operations, processing or product delivery. In contrast to fossil resources, wood resources are dynamic, hence local variation of these efficiencies. They change over time depending on the growth of a given forest stand during a production cycle, which can last several decades and up to one century and more. They also change across space according to the distribution of stands of different development stages in a larger forest area (Section 4.2). Moreover, silvicultural decisions are primarily guided by timber production, while wood fuel is a by-product. They additionally account for other ecosystem services, within the framework of sustainable forest management. Thus, local decisions of WFC management and organisation can highly influence WFC efficiency. Consequently, these decisions are relevant for reaching objectives of energy-transition policies.

#### 4.2 Modelling approach

Our approach has similarities with that of Fortin et al. (2012, 2014), who linked the Fagacées growth model with a carbon accounting tool (CAT) including sub-models of bucking, the production line and wood-product decay. François et al. (2014) used this Fagacées-CAT model as



an input for a gasification plant model, including material flows from the forest and the production line (residuals, recycling). Thus, they assessed plant supply and emissions for different forest management practices, including impacts on forest nutrient exports. However, forest operations between bucking and the production line (e.g. forwarding or seasoning) are not explicitly described. Our study suggests that a more detailed description of material flows and properties as well as task differentiation can provide insights of interest in WFC assessment. Therefore, we consider the two approaches complementary.

The case study showed that our model could provide plausible results for contrasting scenarios of wood fuel supply. Key-variable values were within the orders of magnitude found in the literature, except for ash concentrations that appeared slightly too low (Section 4.1). Moreover, the model proved sensitive to both the amount of wood fuel assigned to trees to be felled (demand sub-scenarios) and the way this wood was supplied to the heating plant (production scale sub-scenarios). Both factors resulted in variation within the WFC in terms of material flows and properties, energy consumption or worktime (Table 2).

The silvicultural schedule was kept constant in the case study. Various schedules could be tested in future studies, since our model is linked to a growth and yield model. This appears relevant given the high variability of EROI depending on the silvicultural intervention (Table 2). Moreover, forest profitability and nutrient-dependent productivity can vary according to silvicultural treatment and harvesting type (Bessaad et al. 2021). Using other growth and yield models would allow for the analysis of further silvicultural options and different tree species. This may include depicting tasks of stand establishment and early development. Such tasks were excluded from the case study because their energy consumptions are primarily dedicated to timber production. They could be modelled based on the generic equations that depict tasks involving machines (Section 2.1.2 and Appendix 1).

The results of our model should be used with caution because it does not yet estimate the precision of its outputs. This would further inform us about the significance of the differences between scenarios. However, accounting for the different sources of uncertainty in forest-wood chain models is a challenging task (Pichancourt et al. 2018). A review by Brunet-Navarro et al. (2016) revealed that only 40% of the models for carbon accounting used uncertainty analysis. This type of analysis seems even rarer in model studies of biomass supply chains (Nunes et al. 2020). Furthermore, validation based on field experiments has hardly been reported (Nunes et al. 2020). Uncertainty in our model can arise from stochastic

components of the growth model in use, from lack of knowledge in task modelling (seasoning and drying), or from variability of input parameter values (Section 2.1.2). Some parameters such as machine performance (production rate) are difficult to estimate as they depend on various factors (Johnson et al. 2012). The parameters of our model were defined so as to reflect relevant data characterising forest operations (Section 2.1). Thus, their variability may be specified based on surveys among forest operators.

Space and time scales should also be considered when interpreting model outputs. The case study results were based on a single forest stand simulated over the long time span (111 years) of an entire forest production cycle. Expecting WFC characteristics such as machine technology and performance to remain unchanged over such a long period is questionable. Our results should rather be interpreted as those of a larger forest area composed of several stands of different ages. In this case, the silvicultural schedule is subdivided into several shorter time spans of a few decades occurring in various stands of different age classes. Yet, stand age classes would be assumed to be equally distributed throughout the forest area—an ideal case rarely found in reality. This limitation may be overcome by connecting our model to new generations of forest landscape models. These models include features of stand growth and yield models. Therefore, they can be used for real-world case studies of large areas associated with forest management planning (Shifley et al. 2017). This would make it possible to tackle issues of spatial and temporal biomass distribution, which is an important factor of supply chain management (Nunes et al. 2020). In this respect, our model appears particularly suitable for scenario analyses aimed at providing recommendations for strategic (or tactic) planning of WFCs. Operational planning would likely require a higher level of detail in the spatial arrangement and timing of tasks (D'Amours et al. 2008).

Providing recommendations requires “Transparency and understanding of the formal reasoning mode of a decision support tool/system by users” (Muys et al. 2010, p 93). Our bottom-up approach favours the understanding of the calculation principles, and thus the interpretation and acceptability of the model outputs. It relies on task sub-models with explicit parameters directly linked to management decisions. Whole-WFC indicators such as EROI, BENE or BEWE are calculated depending on these decisions. Thus, decisions can be evaluated and argued objectively at the local scale, and this can help to implement energy and forest policies (e.g. settlement of a company, guidance of forest management). The development of a graphical user interface may facilitate discussion and consensus building between decision makers

and associated actors. Furthermore, the relative importance of task-related management decisions may be assessed using global sensitivity analysis methods (Cariboni et al. 2007).

Sensitivity analyses may also reveal relevant issues for further model development. The impact of changes in the type and succession of tasks or in the formulation of task sub-models could be tested with our model thanks to its modularity. For instance, consumptions at final harvest were largely driven by motor fuel, with a rather marginal share of the other items (Fig. 6). However, this share may be different in other contexts (Section 4.1). Seasoning and drying models may additionally account for phenomena such as moisture decrease depending on atmospheric conditions, or moisture regain in winter (Filbakk et al. 2011). This would require suitable weather and climate data. In fact, moisture management can be a key driver of supply costs (Kanzian et al. 2016). Accounting for intra-annual variation may also be of interest concerning nutrient export (Ulbricht et al. 2016).

Finally, our model should be associated with economic data such as energy consumption costs or wood fuel quantity and quality benefits. Additional economic assessment would be an important step towards multi-criteria analyses (Buchholz et al. 2009). This may contribute to meet the need for joint assessment of environmental, social and economic criteria (Cambero and Sowlati 2014), and to develop related decision support tools (Kühmaier and Stampfer 2012). Furthermore, our model can be extended to other product types (timber, industry wood). Thus, it may contribute to address sustainability issues of forest operations (Marchi et al. 2018) in a broader sense, including traditional and innovative (Ning et al. 2021) woody biomass valorisations.

## 5 Conclusions

We developed a bottom-up WFC modelling approach relying on inputs from growth and yield modelling, making it possible to consider various silvicultural situations and schedules. Flows of woody material are depicted from forest production to wood fuel delivery to the heating plant. The WFC is composed of individual tasks which can be chosen and linked in a consistent manner. Related management decisions range from silviculture to road transport issues. Thus, energy, nutrient and worktime efficiencies can be assessed for the whole WFC according to various user-defined scenarios.

The case study on European beech suggested that the model could provide plausible results for contrasting scenarios of (i) wood fuel demand and (ii) management-related WFC characteristics (the production scale). High demand associated with large-scale production was most favourable in terms of energy and worktime efficiencies,

but least favourable in terms of nutrient efficiency. Nutrient efficiency was most favourable for moderate demand associated with small-scale production. Furthermore, energy efficiency highly varied according to the type of silvicultural intervention during the forest production cycle. In a larger sense, the case study highlighted that local management decisions all along the WFC highly influenced efficiency indicators, and thus its relevance for energy-transition policies.

The spatio-temporal dynamics of wood fuel production and supply could be studied by running growth models under different silvicultural scenarios. Sensitivity analyses of the WFC as a whole may reveal the most influencing management decisions. Scenario assessment should include further criteria, such as economic ones, and account for the aims and preferences of the actors involved in decision making. Thus, objective discussion and consensus building between actors will be facilitated.

## Appendix 1

### Detailed model description

#### *Input data and deduced wood properties*

Referring to Fig. 1, the growth and yield model provides simulated data about trees cut during different silvicultural interventions throughout a forest production cycle. Essential data are tree species (here: European beech), stand area (ha), number of trees and  $D_g$  (cm). Tree compartment definitions reflect product types according to standard cutting-diameter thresholds. For each tree compartment, dry biomass, nutrient and ash concentrations as well as heating values must be provided.

In our case study on beech, a minimum top-end diameter of 20 cm was required for timber (EN 2012). It was set to 7 cm for industry wood. Wood fuel was bigger or smaller than 7 cm in diameter depending on the chosen assignment (Fig. 3). Tree tops, branches and twigs <7 cm in diameter were also called fine woody debris. Models by Genet et al. (2011) predicted dry biomass (in kg, converted into t) for branches 0–4, 4–7 and  $\geq 7$  cm in diameter, for the whole stem, for the stem  $\geq 7$  cm in diameter, and for the leaves. The dry biomass  $\geq 20$  cm was estimated from the corresponding volume and basic wood density, using the stem taper model from Le Moguédec and Dhôte (2012). Then, the dry biomass of the stem compartments 0–7 and 7–20 cm in diameter were calculated based on the other stem compartments. The wet biomass (t) of the different compartments of standing trees was calculated from their dry biomass assuming a moisture content of 0.5. Models by Wernsdörfer et al. (2014) predicted the concentrations of N, S, P, K, Ca, Mg and Mn ( $\text{g kg}^{-1}$  dry mass) in each tree compartment based on its median diameter. The carbon concentrations

of the different tree compartments were averaged from a database of the INRAE BEF laboratory.

The same database also allowed us to establish models of ash concentration ( $\text{g kg}^{-1}$  dry mass, Eq. 6) and of higher heating value (HHV, in  $\text{kJ kg}^{-1}$  dry mass, Eq. 7):

$$[\text{Ash}] = 2.0345 ([\text{P}] + [\text{K}] + [\text{Ca}] + [\text{Mg}] + [\text{Mn}]) \tag{6}$$

and

$$\text{HHV} = 19,693.87 - 24,541.87 [\text{S}] - 779.71 [\text{Ash}] + 52.39 [\text{C}] [\text{S}] + 1.62 [\text{C}] [\text{Ash}] + 963.26 [\text{S}] [\text{Ash}] - 2.01 [\text{C}] [\text{S}] [\text{Ash}], \tag{7}$$

where squared brackets indicate concentrations. The lower heating value (LHV,  $\text{kJ kg}^{-1}$ ) was calculated from the HHV and the moisture content.

Based on these variables, the nutrient, ash and energy contents were calculated for a given amount of biomass, taking unit conversion into account. Dry mass was assessed at  $65^\circ\text{C}$ , as commonly done in forest science.

**Model settings**

The model settings include general parameters and the methods and tasks parameters (Fig. 1). The parameter values are set by the user. General parameters are applicable to a given WFC scenario to be simulated as a whole. They include forest stand area (ha); light vehicle (car) and machine carrier consumptions ( $\text{kWh km}^{-1}$ ) necessary to bring foresters, machine operators and machines to the stand; the related distance (km) to the workplace (forest stand); the duration of the working day (h).

The settings of the methods and tasks include:

$$\text{outputWetBiomass} = \text{inputWetBiomass} \times \text{materialConservationRatio}, \tag{8}$$

and

$$\text{lossWetBiomass} = \text{inputWetBiomass} \times (1 - \text{materialConservationRatio}) \tag{9}$$

- (1) The Dg-ranges of cut trees, where a maximum of two specific methods can be defined for each range. Using two methods makes sense when at least two silvicultural interventions fall within the Dg-range. In this case, the user sets how many times the first method is applied before moving to the second method;
- (2) The list and succession of tasks to be performed for each method;
- (3) The definition of each task by (a) its type, e.g. felling or forwarding; (b) its name, e.g. chainsaw felling or whole-tree forwarding; and (c) its parameters

related to material flow, energy consumption and worktime.

The first task is automatically fed with the input data from a given silvicultural intervention. Each of the next tasks uses the output of the preceding task as its own input, which is characterised by the product type (e.g. wood fuel) and its form (e.g. log). Felling as well as combined felling and bucking (felling+bucking) tasks include

a Boolean setting in order to specify if trees have leaves or not, depending on the season. Accordingly, leaf biomass is accounted for or set to zero. The felling and bucking tasks can yield several product types (timber, industry wood or wood fuel). The seasoning and drying tasks do not consume any energy.

**Task calculations**

In the following equations, members in italics are parameters, while variables are in upright font. The names of parameters and variables are written out in full to facilitate understanding (e.g. fuelConsumption), unless commonly used abbreviations are available (e.g. HHV for higher heating value).

**Tasks involving machines, apart from transport of wood fuel**

The following applies to the felling, bucking, felling+bucking, bundling, forwarding, chipping and handling (loading) tasks.

Material conservation and the corresponding losses are calculated as follows:

where *materialConservationRatio* (no unit) is a task-specific parameter. For roundwood, the total amount of lost biomass (*lossWetBiomass*) is progressively subtracted from the tree compartments according to their diameter, starting with the thinnest compartments (stem and branches <7 cm). For chips, the lost biomass is evenly distributed among compartments.

Worktimes (h) include machine worktime:

$$\text{machineWorktime} = \frac{\text{wetBiomass}}{\text{machinePerformance}} \tag{10}$$

and human worktime:

$$\text{humanWorktime} = \text{machineWorktime} \times \text{humanToMachineRatio}, \quad (11)$$

where *machinePerformance* (t pmh<sup>-1</sup>) and *humanToMachineRatio* (no unit) are task-specific parameters.

The energy consumption (kWh) of a given task is calculated according to five items: motor fuel (Eq. 12); oil (Eq. 13); transport of operators (Eq. 14); transport of machines (Eq. 15); machine building, maintenance and recycling (BMR, Eq. 16):

$$\text{fuelConsumption} = \text{machineWorktime} \times \text{hourlyFuelConsumption}, \quad (12)$$

$$\text{oilConsumption} = \text{fuelConsumption} \times \text{oilRatio}, \quad (13)$$

$$\text{operatorTransportConsumption} = \frac{\text{humanWorktime}}{\text{workingDayDuration}} \times 2 \times \text{distanceToWorkplace} \times \text{lightVehicleConsumption}, \quad (14)$$

$$\text{machineTransportConsumption} = 2 \times \text{distanceToWorkplace} \times \text{machineCarrierConsumption}, \quad (15)$$

$$\text{BMRConsumption} = \text{machineWeight} \times \text{BMRConsumptionPerWeight} \times \frac{\text{machineWorktime}}{\text{machineLifeTime}}, \quad (16)$$

with the task-specific parameters *hourlyFuelConsumption* (kWh pmh<sup>-1</sup>, with pmh = productive machine hour), *oilRatio* (no unit), *machineWeight* (t) and *machineLifeTime* (pmh), *BMRConsumptionPerWeight* (BMR-related energy consumption (kWh) per machine weight (t)). General parameters are *workingDayDuration* (h), *distanceToWorkplace* (km), *lightVehicleConsumption* (kWh km<sup>-1</sup>) and *machineCarrierConsumption* (kWh km<sup>-1</sup>). Whether *machineTransportConsumption* is calculated or not depends on the Boolean parameter *machineCarrierNeeded*. This parameter specifies if a machine carrier is needed to bring the machine to the workplace. The  $\frac{\text{humanWorktime}}{\text{workingDayDuration}}$  ratio (Eq. 14) gives the number of working days and is rounded up to the closest integer.

The total consumption of a task is the sum of the consumptions of the five items. The total WFC consumption is the sum of the consumptions of all the tasks taken into account.

### Transport of wood fuel

Transport consumption is related to transport distance rather than machine worktime (see above, other tasks involving machines). Wood fuel can be of different material form: whole trees, logs, branches, fine woody debris, bundles or chips. First, the capacity of the device (e.g. road truck) is assessed to determine whether it is limited

by the volume or the mass of the wood fuel to be transported, depending on its bulk density. If the bulk density exceeds the  $\frac{\text{deviceMassCapacity}}{\text{deviceVolumeCapacity}}$  ratio, then the mass is limiting and one trip transports the mass capacity:

$$\text{biomassLoadPerTrip} = \text{deviceMassCapacity} \quad (17)$$

Otherwise, the volume is limiting and the biomass load per trip is:

$$\text{biomassLoadPerTrip} = \text{deviceVolumeCapacity} \times \text{biomassBulkDensity}. \quad (18)$$

Based on the number of round trips:

$$\text{numberOfRoundTrips} = \frac{\text{wetBiomass}}{\text{biomassLoadPerTrip}} \quad (19)$$

and on round trip consumption:

$$\text{roundTripConsumption} = \text{deliveryDistance} \times (\text{deviceConsumptionFull} + \text{deviceConsumptionEmpty}), \quad (20)$$

total motor-fuel consumption is calculated as:

$$\text{fuelConsumption} = \text{numberOfRoundTrips} \times \text{roundTripConsumption}. \quad (21)$$

Task-specific parameters are as follows: *deviceMassCapacity* (t), *deviceVolumeCapacity* (m<sup>3</sup>), *biomassBulkDensity* (t m<sup>-3</sup>), *deliveryDistance* (km), *deviceConsumptionFull* (kWh km<sup>-1</sup>) and *deviceConsumptionEmpty* (kWh km<sup>-1</sup>). The  $\frac{\text{wetBiomass}}{\text{biomassLoadPerTrip}}$  ratio (Eq. 19) is rounded up to the closest integer.

Oil consumption is assessed according to Eq. 13. BMR consumption is calculated as:

$$\text{BMRConsumption} = \text{deviceWeight} \times \text{BMRConsumptionPerWeight} \times \frac{2 \times \text{deliveryDistance}}{\text{deviceLifeDistance}}, \quad (22)$$

with the task-specific parameters *deviceWeight* (t), *BMRConsumptionPerWeight* (kWh t<sup>-1</sup>) and *deviceLifeDistance* (km). This latter parameter reflects the maximum total distance that the device can cover before being replaced. In a similar manner, the parameter *machineLifeTime* is used for the other tasks involving machines (Eq. 16).

Worktimes of humans and machines are assumed to be equal. They are assessed as:

$$\text{humanWorktime} = \text{machineWorktime} = \text{numberOfRoundTrips} \times \frac{2 \times \text{deliveryDistance}}{\text{deviceAverageSpeed}}, \quad (23)$$

where *deviceAverageSpeed* (km h<sup>-1</sup>) is a task-specific parameter.

No operator or machine transport is considered here.

### Seasoning and drying

Seasoning and drying are passive processes of moisture and dry biomass losses, considering their duration (*durationMonths*, in number of months) and pile sheltering (covered or uncovered). The moisture content in percent (moistureContentPC) is assessed iteratively for covered piles as:

$$\text{moistureContentPC}_{t+1} = -0.0091 \times \text{moistureContentPC}_t^2 + 1.3782 \times \text{moistureContentPC}_t - 4.3961 \tag{24}$$

and for uncovered piles as

$$\text{moistureContentPC}_{t+1} = -0.0121 \times \text{moistureContentPC}_t^2 + 1.6804 \times \text{moistureContentPC}_t - 9.9131, \tag{25}$$

with  $\text{moistureContentPC}_t = 100 \times \text{moistureContent}_t$  and  $t = 0, 1, 2, \dots, \text{durationMonths} - 1$ .

Dry biomass losses are assessed as:

$$\text{lossDryBiomass} = \text{materialLossRatio} \times \text{durationMonths} \times \text{inputDryBiomass}, \tag{26}$$

where the *materialLossRatios* are assumed to be 0.005 and 0.01 for covered and uncovered piles during seasoning, respectively, and 0.01 and 0.02 for covered and uncovered piles during drying, respectively. The lost biomass is distributed among tree compartments as described above for tasks involving machines. A Boolean

parameter (*pileCoverage*) specifies if piles are covered or not.

### Bucking rules

Bucking relies on four parameters. Three parameters define the product types of the stem (timber, industry wood or wood fuel), of the branches without fine woody debris (industry wood or wood fuel or unharvested) and of fine woody debris (wood fuel or unharvested). A Boolean parameter specifies if branches are crosscut in order to separate fine woody debris or not. Depending on these parameters, Table 3 shows the resulting material form (logs, branches or fine woody debris) and associated tree compartments. Please note that tree compartment definitions according to their diameter are those for European beech. They may partly differ for other species. Furthermore, harvesting whole trees is not considered here as this only requires the felling task.

## Appendix 2

### User-defined parameters of the case study

The bucking parameters used in the case study are highlighted in Table 3. The parameter values in Tables 4, 5, 6 and 7 apply to tasks of wood fuel production and supply, excluding timber- and industry-wood-related tasks.

**Table 3** Bucking parameters and resulting tree compartment assignment and material form. Bucking of branches is a Boolean parameter that specifies if branches are cut at the 7-cm-diameter limit or not (FWD = fine woody debris, <7-cm diameter over bark). The bucking rules applied in the case study are highlighted in italics

Bucking parameter				Resulting tree compartment assignment and material form			
Product type of stems	Bucking of branches (Boolean)	Product type of branches <sup>a</sup>	Product type of FWD	Stem ≥ 20 cm	Stem [7, 20[ cm	Branches ≥ 7 cm	Stem and branches < 7 cm
TIMBER	True	INDUSTRY	FUEL	LOGS	LOGS -----		FWD
TIMBER	True	INDUSTRY	Unharvested	LOGS	LOGS -----		
TIMBER	True	FUEL	FUEL	LOGS	LOGS -----		FWD
<i>TIMBER</i>	<i>True</i>	<i>FUEL</i>	<i>Unharvested</i>	<i>LOGS</i>	<i>LOGS -----</i>		
<i>TIMBER</i>	<i>False</i>	<i>FUEL</i>	<i>FUEL</i>	<i>LOGS</i>	<i>BRANCHES -----</i>		
<i>TIMBER</i>	<i>False</i>	<i>Unharvested</i>	<i>Unharvested</i>	<i>LOGS</i>			
INDUSTRY	True	INDUSTRY	FUEL	LOGS -----			FWD
INDUSTRY	True	INDUSTRY	Unharvested	LOGS -----			
INDUSTRY	True	FUEL	FUEL	LOGS -----		LOGS	FWD
INDUSTRY	True	FUEL	Unharvested	LOGS -----		LOGS	
INDUSTRY	False	FUEL	FUEL	LOGS -----		BRANCHES -----	
<i>INDUSTRY</i>	<i>False</i>	<i>Unharvested</i>	<i>Unharvested</i>	<i>LOGS -----</i>			
FUEL	True	FUEL	FUEL	LOGS -----			FWD
FUEL	True	FUEL	Unharvested	LOGS -----			
FUEL	False	FUEL	FUEL	LOGS -----		BRANCHES -----	
FUEL	False	Unharvested	Unharvested	LOGS -----			

<sup>a</sup> ≥ 7 cm in diameter



**Table 4** User-defined parameters of the HighLarge scenario (referring to the model description in Appendix 1)

<b>General parameters</b>		<b>Task-specific parameters of seasoning</b>	
standArea	lightVehicleConsumption	workingDayDuration	distanceToWorkplace
(ha)	(kWh km <sup>-1</sup> )	(h)	(km)
5	0.6	3.5	30
		7	
<b>Task-specific parameters of felling, combined felling and bucking, forwarding and chipping</b>		<b>Task-specific parameters of seasoning</b>	
Dg (cm) range	Method	Task <sup>a</sup>	materialConservationRatio
			(no unit)
[8, 25[	1	Felling	0.9
		Forwarding	0.9
	2	Felling	0.9
		Forwarding	0.9
[25, 100[	3	Felling	0.9
		Forwarding	0.9
	4	Fell+ buck <sup>b</sup>	0.9
		Forwarding	0.9
[8, 100[	1–4	Chipping	0.9
<b>Task-specific parameters of transport</b>		<b>Task-specific parameters of seasoning</b>	
Dg (cm) range	Method	deviceVolumeCapacity	deviceMassCapacity
		(m <sup>3</sup> )	(t)
[8, 100[	1–4	90	30
<b>Task-specific parameters of seasoning</b>		<b>Task-specific parameters of seasoning</b>	
pileCoverage	durationMonths	BMRConsumptionPerWeight	machineLifeToMachineRatio
(Boolean)	(number of months)	(kWh t <sup>-1</sup> )	(no unit)
false	6	16,556	1.3
		16,556	1.2
		16,556	1.3
		16,556	1.2
		16,556	1.17
		4000	1.2
		20,000	1.17
		4000	1.2
		20,000	1.17
		16,556	1.2
		16,556	1.43
<b>Task-specific parameters of seasoning</b>		<b>Task-specific parameters of seasoning</b>	
BMRConsumptionPerWeight	deviceLifeDistance	deviceAverageSpeed	deliveryDistance
(kWh t <sup>-1</sup> )	(km)	(km h <sup>-1</sup> )	(km)
16,556	1,500,000	68	91

<sup>a</sup> Felling was applied to trees without leaves (winter season)

<sup>b</sup> Combined felling and bucking



**Table 5** User-defined parameters of the HighSmall scenario (referring to the model description in Appendix 1)

<b>General parameters</b>		<b>Task-specific parameters of felling, combined felling and bucking, forwarding and chipping</b>		<b>Task-specific parameters of seasoning</b>							
standArea	lightVehicleConsumption	machineCarrierConsumption	workingDayDuration	distanceToWorkplace	pileCoverage	durationMonths					
(ha)	(kWh km <sup>-1</sup> )	(kWh km <sup>-1</sup> )	(h)	(km)	(Boolean)	(number of months)					
5	0.6	3.5	7	5	false	6					
Dg (cm) range	Method	Task <sup>a</sup>	materialConservationRatio	machinePerformance	hourlyFuelConsumption	oilRatio	machineWeight	BMRConsumptionPerWeight	machineLifeTime	humanToMachineRatio	machineCarrierNeeded
[8, 25[		Felling	(no unit)	(t pmh <sup>-1</sup> )	(kWh pmh <sup>-1</sup> )	(no unit)	(t)	(kWh t <sup>-1</sup> )	(pmh)	(no unit)	(Boolean)
		Forwarding	0.9	3.03	493.5	0.058	27	16,556	20,000	1.3	True
		Felling	0.7	4.75	195.3	0.033	6.5	16,556	20,000	1.2	True
		Forwarding	0.9	6	441	0.058	20.1	16,556	20,000	1.3	True
		Forwarding	0.7	4.75	195.3	0.033	6.5	16,556	20,000	1.2	True
[25, 100[		Felling	0.9	9.5	10.5	0.322	0.006	16,556	4000	1.17	False
		Forwarding	0.7	4.25	195.3	0.033	6.5	16,556	20,000	1.2	True
		Fell+ buck <sup>b</sup>	0.9	12.7	10.5	0.322	0.006	16,556	4000	1.17	False
		Forwarding	0.7	4.25	139.5	0.033	6.5	16,556	20,000	1.2	True
[8, 100[		Chipping	0.9	6.3	223.2	0.02	12.7	16,556	20,000	1.22	True
Dg (cm) range	Method	deviceVolumeCapacity	deviceMassCapacity	BiomassBulkDensity	DeviceConsumptionFull	oilRatio	deviceWeight	BMRConsumptionPerWeight	deviceLifeDistance	deviceAverageSpeed	deliveryDistance
[8, 100[	1-4	(m <sup>3</sup> )	(t)	(t m <sup>-3</sup> )	(kWh km <sup>-1</sup> )	(no unit)	(t)	(kWh t <sup>-1</sup> )	(km)	(km h <sup>-1</sup> )	(km)
		31	17.6	0.3	11.21	0.0008	11.6	16,556	300,000	15	5

<sup>a</sup> Felling was applied to trees without leaves (winter season)

<sup>b</sup> Combined felling and bucking

**Table 6** User-defined parameters of the Moderatelarge scenario (referring to the model description in Appendix 1)

General parameters			Task-specific parameters of seasoning								
standArea	lightVehicleConsumption	machineCarrierConsumption	workingDayDuration	distanceToWorkplace	pileCoverage	durationMonths					
(ha)	(kWh km <sup>-1</sup> )	(kWh km <sup>-1</sup> )	(h)	(km)	(Boolean)	(number of months)					
5	0.6	3.5	7	30	False	6					
Task-specific parameters of felling, combined felling and bucking, forwarding and chipping											
Dg (cm) range	Method	Task <sup>a</sup>	materialConservationRatio	hourlyFuelConsumption	oilRatio	machineWeight	machineLifeTime	humanToMachineRatio	machineCarrierNeeded		
[8, 17]	1	Felling	(no unit)	(kWh pmh <sup>-1</sup> )	(no unit)	(t)	(pmh)	(no unit)	(Boolean)		
		Forwarding	0.9	493.5	0.058	27	20,000	1.3	True		
		Chipping	0.9	298.9	0.033	13.73	20,000	1.2	True		
[35, 100]	2	Fell+ buck <sup>b</sup>	0.9	573	0.02	26	20,000	1.43	True		
		Forwarding	1	10.5	0.322	0.006	4000	1.17	False		
		Chipping	0.9	298.9	0.033	13.73	20,000	1.2	True		
				573	0.02	26	20,000	1.43	True		
Task-specific parameters of transport											
Dg (cm) range	Method	deviceVolumeCapacity	deviceMassCapacity	BiomassBulkDensity	DeviceConsumptionFull	oilRatio	deviceWeight	BMRConsumptionPerWeight	deviceLifeDistance	deviceAverageSpeed	deliveryDistance
[8, 17]; [35, 100]	1-2	(m <sup>3</sup> )	(t m <sup>-3</sup> )	(t m <sup>-3</sup> )	(kWh km <sup>-1</sup> )	(no unit)	(t)	(kWh t <sup>-1</sup> )	(km)	(km h <sup>-1</sup> )	(km)
		90	0.3	0.3	6.435	0.0008	27	16,556	1,500,000	68	91

<sup>a</sup> Felling was applied to trees without leaves (winter season)

<sup>b</sup> Combined felling and bucking

**Table 7** User-defined parameters of the Moderatesmall scenario (referring to the model description in Appendix 1)

General parameters			Task-specific parameters of seasoning									
standArea	lightVehicleConsumption	machineCarrierConsumption	workingDayDuration	distanceToWorkplace	pileCoverage	durationMonths						
(ha)	(kWh km <sup>-1</sup> )	(kWh km <sup>-1</sup> )	(h)	(km)	(Boolean)	(number of months)						
5	0.6	3.5	7	5	False	6						
Task-specific parameters of felling, combined felling and bucking, forwarding and chipping												
Dg (cm) range	Method	Task <sup>a</sup>	materialConservationRatio	machinePerformance	hourlyFuelConsumption	oilRatio	machineWeight	BMRConsumptionPerWeight	machineLifeTime	humanToMachineRatio	machineCarrierNeeded	
			(no unit)	(t pmh <sup>-1</sup> )	(kWh pmh <sup>-1</sup> )	(no unit)	(t)	(kWh t <sup>-1</sup> )	(pmh)	(no unit)	(Boolean)	
[8, 17]	1	Felling	0.9	3.03	493.5	0.058	27	16,556	20,000	1.3	true	
		Forwarding	0.7	4.75	195.3	0.033	6.5	16,556	20,000	1.2	true	
		Chipping	0.9	6.3	223.2	0.02	12.7	16,556	20,000	1.22	true	
[35, 100]	2	Fell+buck <sup>b</sup>	0.9	5.1	10.5	0.322	0.006	16,556	4000	1.17	false	
		Forwarding	1	2.2	139.5	0.033	6.5	16,556	20,000	1.2	true	
		Chipping	0.9	6.8	223.2	0.02	12.7	16,556	20,000	1.22	true	
Task-specific parameters of transport												
Dg (cm) range	Method	deviceVolumeCapacity	deviceMassCapacity	BiomassBulkDensity	DeviceConsumptionFull	DeviceConsumptionEmpty	oilRatio	deviceWeight	BMRConsumptionPerWeight	deviceLifeDistance	deviceAverageSpeed	deliveryDistance
		(m <sup>3</sup> )	(t)	(t m <sup>-3</sup> )	(kWh km <sup>-1</sup> )	(kWh km <sup>-1</sup> )	(no unit)	(t)	(kWh t <sup>-1</sup> )	(km)	(km h <sup>-1</sup> )	(km)
[8, 17]; [35, 100]	1-2	31	17.6	0.3	13.08	11.21	0.008	11.6	16,556	300,000	15	5

<sup>a</sup> Felling was applied to trees without leaves (winter season)

<sup>b</sup> Combined felling and bucking

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### Code availability

The code of the model presented underlies the charter of the CAPSIS software platform managed by INRAE (<https://capsis.cirad.fr/capsis/charter>, visited on 19 December 2022).

### Authors' contributions

NB designed and implemented the model as well as the simulation study; CD contributed to model design and provided expert knowledge on forest management; LS-A contributed to model design and provided expert knowledge on nutrient export; YR provided expert knowledge on energy science and co-supervised the PhD work of NB; MF provided expert knowledge on wood science, co-supervised the PhD work of NB and acquired funding; HW co-supervised the PhD work of NB, conceptualised with him the present paper, and contributed to simulation and analysis; all authors contributed to manuscript writing or provided constructive comments on the model or case study. The author(s) read and approved the final manuscript.

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### Availability of data and materials

The dataset providing the results of the present study is available from the corresponding author on reasonable request.

### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

All authors gave their informed consent to this publication.

#### Competing interests

The authors declare that they have no competing interests.

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